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VACUUM SWITCHGEAR

A SURVEY

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VACUUM SWITCHGEAR

A SURVEY

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Technology Utilization Division
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Foreword

Although men have considered operating electrical switches in vacuum for many years, there is no such switching gear in today's big power installations. Vacuum switches might be better in several respects than the switches now used. Technological advances resulting from National Aeronautics and Space Administration programs may be helpful in reducing the cost and increasing the reliability of vacuum switches.

NASA is required to make those of its findings which appear to have industrial potentialities widely and appropriately available. Dr. W. S. Emmerich prepared this report for the NASA Office of Technology Utilization to point out some such potentialities and guide persons wishing to explore them further.

George Howick, *Director,*
Technology Utilization Division
National Aeronautics and Space Administration

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Contents

Acknowledgments

In drafting this survey, the author has relied on the literature and the reports furnished by NASA. None of the techniques discussed is original with the author, who has attempted to report as faithfully as possible the work of others. If the results of some NASA investigators were not included or were unintentionally modified in the process of transcription, the author wishes to apologize for such omissions and transgressions.

To keep the report from being unduly complex, the reproduction of numerical, mathematical, and highly technical material has been minimized. Readers wishing more details may find it beneficial to obtain copies of the cited reports. The excellent literature retrieval systems which are available, such as those the NASA Scientific and Technical Information Division maintains, should make it easier than it formerly was to obtain individual reports.

CHAPTER 1

A Switching Problem

On the afternoon of November 9, 1965, shortly after 5 o'clock, most of the northeastern United States experienced the largest electric power failure in history. The power was lost from a few minutes in some locations to more than half a day in others. Occurring during a time of day when there is a peak demand for power in this area of great population density, it offered the greatest potential for havoc.

It all started when at 5:16:11 p.m., a circuit breaker disconnected one of five extra-high-voltage lines that carry power from Niagara Falls toward Toronto. The circuit breakers on each of these lines were set to operate at approximately 375 Mw in order to detect faults beyond the next switching point, although the load-carrying capacity of the lines is considerably larger. Personnel operating the system were not aware that the circuit-breaker relay was set at this level and when the average power flow reached 356 Mw, the normal fluctuations that occur from moment to moment caused the breaker to operate and shift the load to the other lines, which tripped out in a similar manner within about $2\frac{1}{2}$ seconds.

With the dropping of the lines to Toronto, approximately 1500 Mw of power being generated at Niagara became superimposed on the lines leading to the South and the East. The instantaneous result was an acceleration of the generators at Niagara, putting them out of phase with most of the other generation attached to the interconnected transmission system and this transient condition was directly responsible for the breakup of the New York State backbone transmission system. Within 4 seconds, protective circuit breakers completely disconnected the powerlines from Niagara, leaving a generator deficiency of 1100 Mw which was draining the power resources of the New England and southeast New York area. Generation reserves were not adequate to meet this additional demand on short notice, and the power frequency began to sag. This created a cascade effect so that the steam plants in New England and the New York City area had to be shut down one after the other to forestall damage and destruction.

Having isolated the systems, it was necessary, in preparation for restoring electric service, to make sure that circuit breakers and other equipment were in operational condition. As power became available again, it was essential that the various load centers be switched on in a careful, sectionalized synchronized manner. It was then possible, by use of additional switching equipment, to restore connection with the remaining network.

Only a single isolated series of events has been cited here to point out the important functions that circuit breakers and switching installations are called upon to perform in the control, transmission, and distribution of electric power. Innumerable switching operations are completed daily without such dramatic consequences. The particular example chosen here shows that these operations have a much greater importance than the public realizes and that it may be worthwhile to investigate whether new approaches to this problem could result in even more reliable, more convenient and perhaps less expensive equipment.

A circuit-breaker installation is a complicated machine combining both electrical and mechanical devices. The principal electrical component is the circuit interrupter, the function of which is to disconnect the powerline even when the largest possible current is flowing, and to establish sufficient electrical insulation to insure complete isolation from the high voltage of the line. In the performance of this function, a number of electrical characteristics must be considered when the interrupter is closed, when it is open, and when it is arcing; i.e., in the interrupting stage. For each characteristic, a rating is established.

When the interrupter is closed, it is asked to carry a *continuous current* as well as a *momentary current,* the latter usually defined for a given time period, say, 1 second, since it may happen occasionally that a circuit breaker is asked to pass a large surge current without interruption. When the interrupter is open, it is asked to hold off a *withstand voltage,* usually given for a limited period of time, and it is asked to pass a *BIL* test, consisting of withstanding a pulse of voltage of mutually agreed wave shape. When the interrupter is activated, it is asked to interrupt the *interrupting current* at the *interrupting voltage.* Ratings for additional properties may be given, such as the rate of rise of the recovery voltage following the interruption process. All of these ratings except BIL are specified either for dc or for a fixed ac frequency, usually 50–60 hertz.

Circuit interrupters can be classified according to the medium in which the interruption takes place, such as air, sulfurhexafluoride, oil, or vacuum. The first three media are used extensively throughout the industry today, whereas vacuum interrupters have come on the market only recently in relatively modest ratings. In principle, the vacuum interrupter could have a number of good features. Among them are the following:

A. *Efficient:*
   1. Long service life
   2. Little deterioration of the contacts
B. *Fireproof:*
   1. Nothing to burn
   2. Safe to install anywhere
C. *No Ground Shock:*
   1. Needs no special foundation
   2. Compact and easy to install
D. *Little Maintenance:*
   1. Contacts are hermetically sealed
   2. Operation is virtually silent
E. *Explosionproof:*
   1. No generation of high-pressure gases
   2. No implosion
F. *Fast Action:*
   1. Arcing time, ½ cycle
   2. Short stroke distance

Why, then, have not vacuum circuit breakers been manufactured more extensively in the past, and why are they not in general service today? The answer will be evident from this report.

Since the days of pioneering studies of vacuum circuit breakers, high-speed pumps have become available and vacua on the order of 10^{-8} to 10^{-10} torr now can be obtained as a matter of routine. The progress made in vacuum technology even before the advent of the NASA programs has contributed considerably to solving the basic problems of the early vacuum switches. As will be seen later, the main ways in which the NASA advances can contribute to these areas of technology are to decrease the cost of production and to increase the reliability. The rapid development of vacuum technology in the last 10 or 15 years and the interest that the exploration of outer space has caused in scientific circles now makes it possible to seriously consider vacuum switches with the required properties.

The next 20 years may see a considerable development in vacuum circuit breakers and it is not inconceivable that vacuum switchgear will be used for many circuit-breaker applications. The simultaneous and so far unrelated efforts of NASA to develop high vacuum technology happen to coincide with the interests of the electrical industry in this field and therefore one may expect overlap in technology and exchange of information in the extremely high vacuum field.

HISTORICAL REVIEW

In 1926 Prof. R. W. Sorenson reported experimental results with vacuum switching (ref. 1). His paper reviewed the history of the subject and discussed both the pioneering studies of the vacuum switch and some of the later engineering applications. Even then it was obvious that the vacuum interrupter had certain advantages over more conventional switches. The relatively small size of the interrupting units and mechanisms which are possible, due to the very high breakdown strength in vacuum for short gaps, is one of these advantages. Furthermore, the absence of gaseous material in the discharge allows extremely rapid switching, typically much faster than a half cycle of 60-cycle alternating current. Vacuum switches, therefore, have found applications in capacitor discharges, high-frequency apparatus, and other specialty items, and a line of vacuum switches has been manufactured commercially by the Jennings Radio Co. and other companies (ref. 2).

Shortly after the review by Professor Sorenson, the General Electric Co. purchased patent rights from the California Institute of Technology and began a limited development program, but terminated it in 1931. Several important areas of vacuum technology had not been developed sufficiently at that time. A high-power vacuum interrupter, completely sealed and capable of operating over extensive periods of time, could not be developed without new technologies and scientific advances in a number of fields related to high vacuum. Undoubtedly the work that has been done by NASA and under contracts for NASA as well as other Government agencies has already contributed greatly to the issue at hand and there is no doubt that the research being continued will have an enormous influence on the commercial development of the vacuum circuit interrupter.

The outstanding shortcomings and weaknesses in the older vacuum switches can be traced to the following:

(1) *Insufficiently developed vacuum technology.*—This includes glass-to-metal seals capable of withstanding the stress of high short-circuit currents, and vacuum techniques capable of producing the high degree of degassing of metals which is necessary for long life in a field breaker.

(2) *Large amounts of gas evolved from the electrodes during arcing at high currents.*—These accumulate in the vessel and destroy the vacuum.

(3) *Severe surge voltages,* due to current chopping, when refractory metal such as tungsten or molybdenum is employed in the electrodes exclusively.

(4) *Electrode welding.*—The highly cleaned surfaces of the electrodes produce strong welds in vacuum, often with normal contact pressures even in the absence of electric current.

(5) *Inconsistent performance* for reasons that could not be identified.

Any one of these weaknesses could have condemned a device for large-scale application in the utility industry, where reliable equipment is essential. Nevertheless, it was possible to develop prototypes in the laboratory which were able to interrupt on the order of 5000 amperes of current at a line voltage of 14½ kV, one of the standard electric utility distribution conditions.

The rapid development of the high-vacuum and ultra-high-vacuum fields in the 1950's revived hope that an interrupter of this type eventually could be made to work under more severe conditions. Consequently, a program was started under J. D. Cobine of the General Electric Co., which led in 1961 to the first large-scale vacuum interrupter for the electric utility market. Although very large (figs. 1, 2, and 3), this market is only one of several possibilities. The successful development of such a switch suggests that other markets may be exploited, too.

UNSOLVED PROBLEMS AND REQUIREMENTS

Among the unsolved problems, maintaining the reliability of the high vacuum, is clearly one that should receive a large amount of attention. Efforts spent on the remaining problems would be of little use if the vacuum could not be maintained in a sealed-off container.

The technology for producing large glass-to-metal seals in ignitrons and large transmitting tubes is now satisfactory and is being used in the manufacture of these products. Large Kovar seals to glass and similar materials permit the design of seals capable of withstanding the mechanical and thermal stresses which must be expected in high-power applications. Furthermore, high-vacuum technology is sufficiently advanced that large-capacity, high-speed pumps have become available and pressures on the order 10^{-8} to 10^{-10} torr can be obtained as a matter of routine. NASA advances now may be helpful in making the vacuum switch more competitive and enlarging its market coverage.

A second consideration of extreme importance in vacuum circuit breakers, namely, the evolution of gas from within the electrodes caused by erosion of the arc, has long been a crucial problem. Although the refractory metals such as tungsten and molybdenum can be outgassed by processing at high temperature, the unfavorable thermionic conditions and simultaneously poor chopping habits of these materials would ultimately limit their use in vacuum switches to currents below a few thousand amperes. Gas evolution must be kept to a very small degree for a vacuum breaker to operate successfully over long periods of time. To keep the pressure below 10^{-5} torr under arcing conditions where a great deal of erosion of the electrodes occurs, it is necessary to have contact metals which contain less than 1 part per 10 million of noncondensable gases or impurity compounds that can dissociate into noncondensable gases.

It is well known that gas-free metals, such as copper, can be made by drawing single crystals of the material. The technology which has been developed in drawing germanium, silicon, and other semiconducting materials is of considerable help. It has been observed that single crystals of copper do indeed produce contacts which are perfectly serviceable in a vacuum switch, but the cost of such single crystals drawn from a melt is prohibitive for large-scale manufacture. This is, however, not the only way in which gas can be removed from materials. It is also possible to produce a metal that has less than 1 part in 10 million of such gases by zone refining. This process, although expensive in small batches, lends itself to manufacturing techniques considerably better than the first method mentioned, and it has been possible to produce copper with a gaseous impurity concentration of the order of one part in a billion (ref. 3).

It has been found further that the zone refining methods can be modified, and that with the advent of extremely fast pumping techniques and proper handling of the material, it is possi-

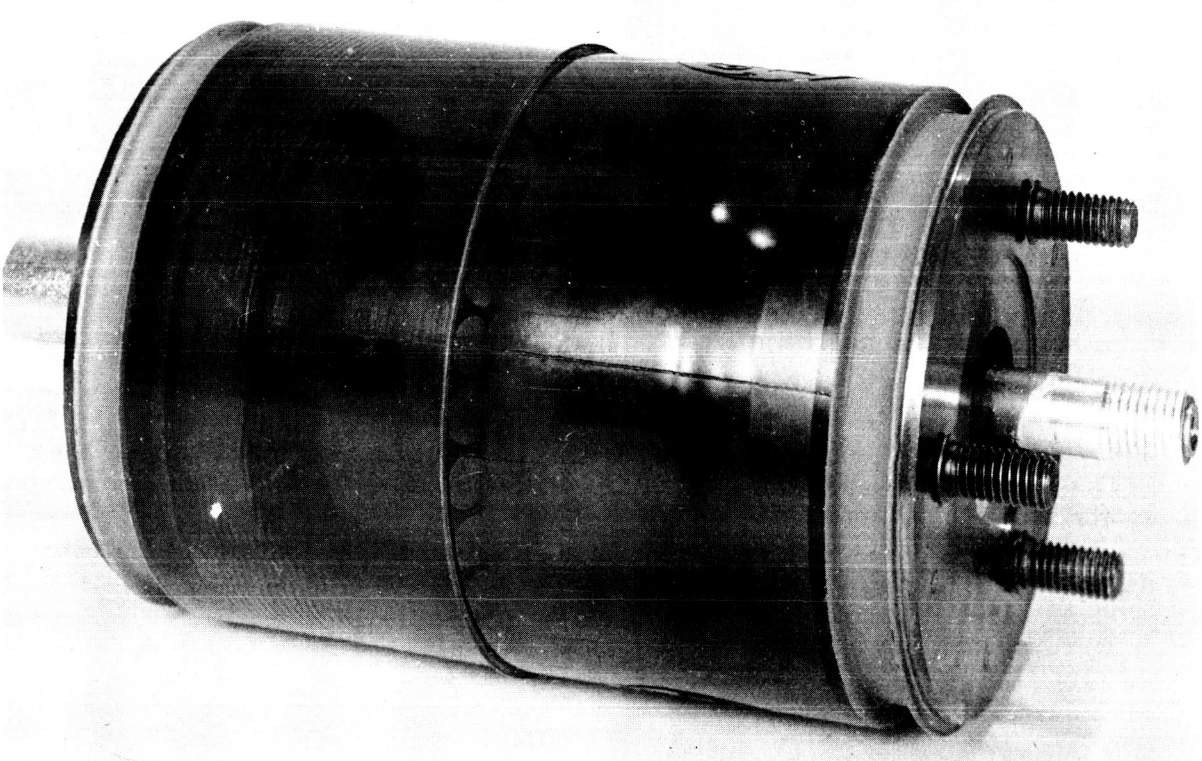

FIGURE 1.—General Electric Power-Vac Vacuum Interrupter Model PV–01.

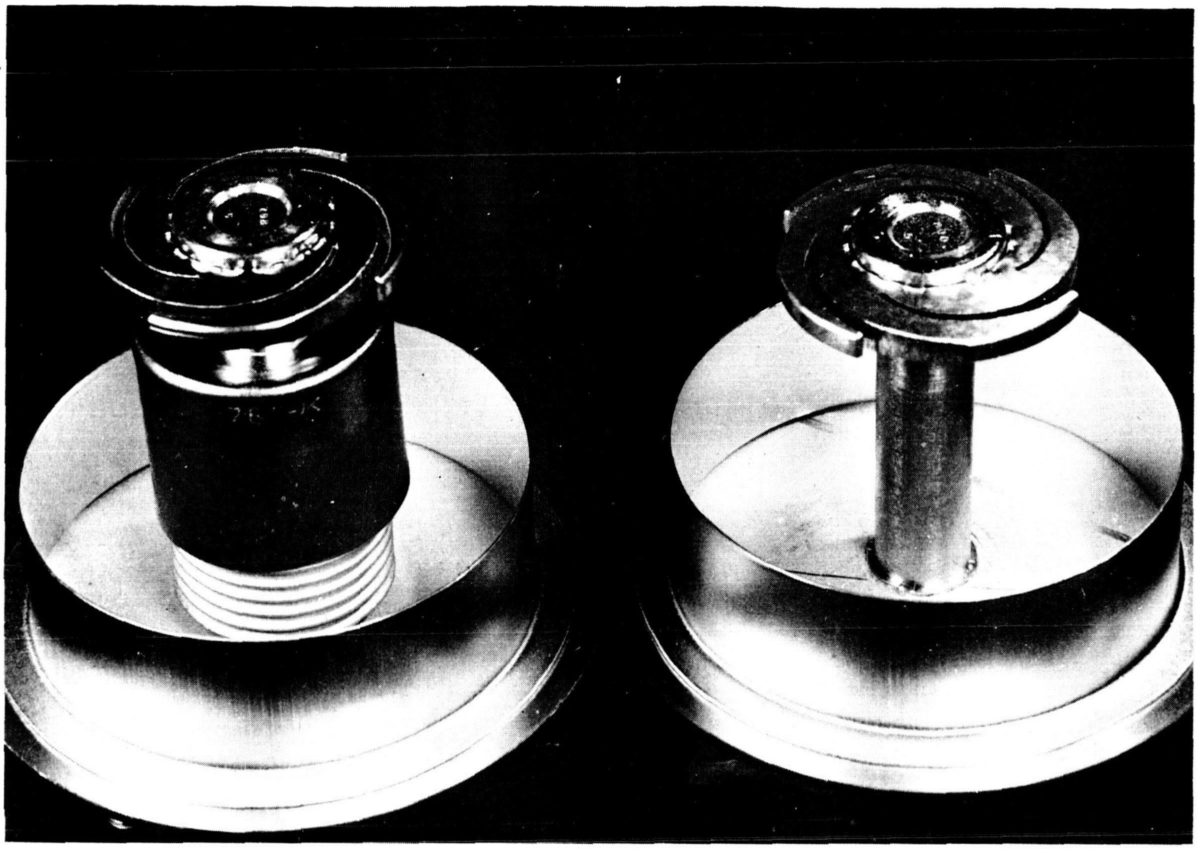

FIGURE 2.—Electrode assemblies for the PV–01 Power-Vac Interrupter shown in figure 1.

ble to obtain copper from which the gases have been removed sufficiently for vacuum switch application. Thus, it appears possible to develop electrodes for vacuum circuit breakers that are sufficiently gas free. The methods at our disposal are more or less expensive and the work that NASA has done will have to be correlated with the state of the art in this general area. Undoubtedly, further advances are possible.

A third factor in the construction and performance of vacuum switches is the way in which the metallic vapors are condensed and how they interact with the surrounding structure. During the arcing in a vacuum switch, material from the electrodes is constantly evaporated into the interelectrode space. The pressure prevailing under typical arcing conditions may exceed several atmospheres. But once the source of current is shut off, which happens during current zero of alternating current, production of the metallic vapor ceases and whatever quantity is left in the space between the electrodes condenses out on the electrode surfaces and surrounding structures. The speed with which the vapor is removed determines not only the steady-state conditions during arcing, and the ultimate pressure reached during these conditions, but also the recovery capabilities of the switch. In typical switching operations, especially where inductive loads occur, very steep transients are produced. They tend to restrike or arc back between the electrodes and other structures, thus causing the switch to fail. Hence, rapid removal not only lowers the pressure during arcing but improves the performance of the switch after the arc is extinguished. The most obvious solution to this problem is to surround the electrode space with a metallic shield on which the metallic vapor can condense. This requirement, therefore, necessitates study of metallic surfaces

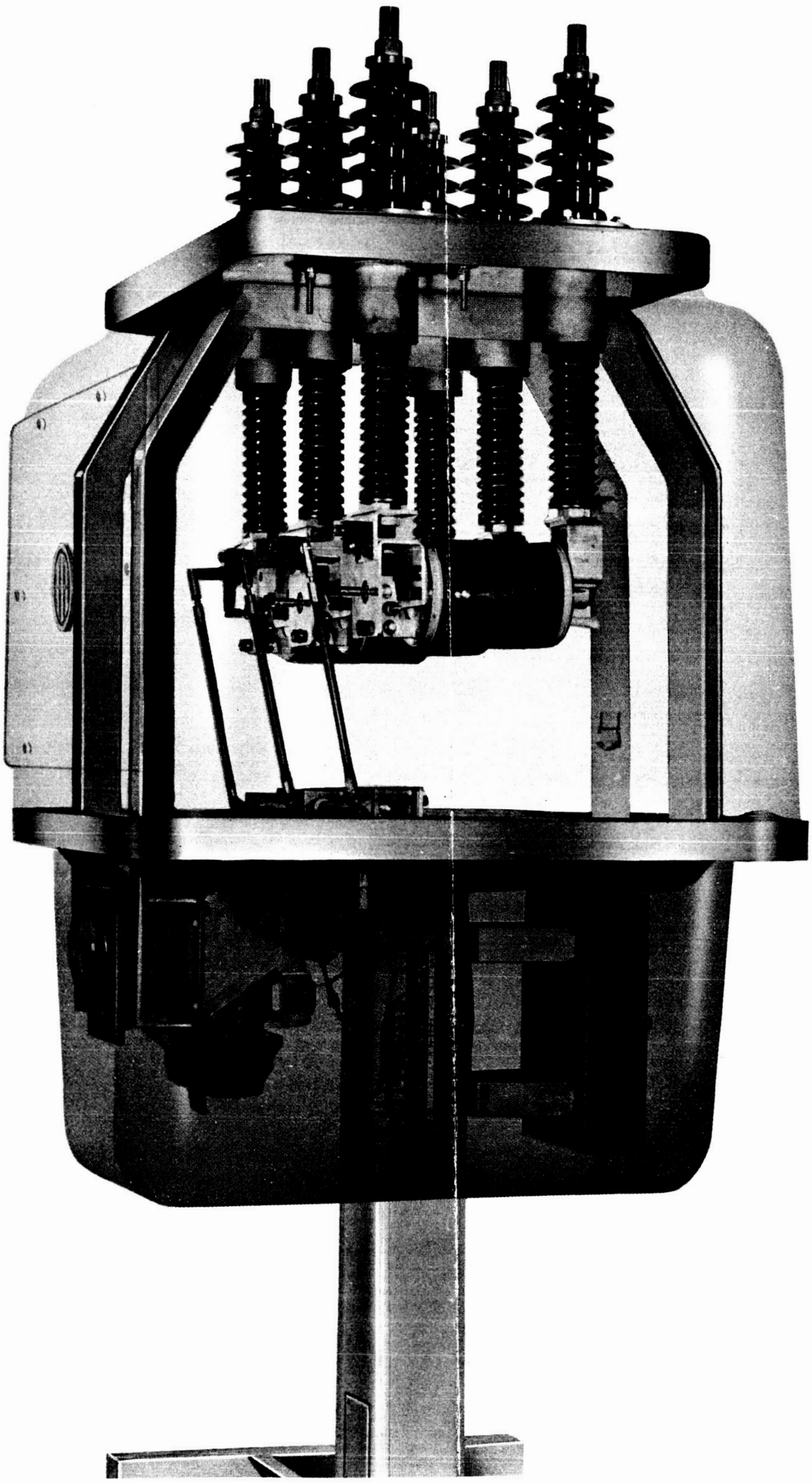

FIGURE 3.—Power class III recloser: Breaker manufactured by I-T-E Circuit Breaker Co. utilizing the Power-Vac interrupter shown in figure 1.

and the way in which metallic vapor is condensed on them. The principle is similar to that used in the vac-ion-pump, which has been studied by NASA and will be discussed later in this report.

A fourth factor in the proper operation of a vacuum switch concerns the magnetic fields which are produced by the current that flows through the switch or by externally applied magnetic fields. Although important, magnetic considerations will only be mentioned parenthetically in this survey.

Finally, an important engineering problem, intimately related to NASA work, is cold welding upon contact and welding under arcing conditions. In the vacuum interrupter, the conditions of the electrode surfaces are ideal for welding because no surface oxides or other contaminants are present. These conditions are far different from those found in air or other media, and a different approach to contact material selection and design is necessary. A material is needed that simultaneously has three desirable properties: good high current interruption performance, good dielectric characteristics, and good antiwelding properties. Numerous materials have one or the other, perhaps two or more, of these characteristics, and the chances are good that a material can be obtained which is capable of performing the function required in a vacuum power interrupter. The antiwelding property is closely related to lubrication problems in space. Furthermore, it is desirable, although not essential, to incorporate systems having mechanical linkages in vacuum interrupters. Again we fall back on the NASA technology.

A further area of interaction between the development of a vacuum-switch program and the interests of NASA is in vacuum diagnostic techniques. Magnetic fields due to the high currents in the vacuum interrupter produce distortions in the transient-pressure response of ordinary ionization gauges. This effect was overcome in the hot cathode magnetron ionization gauge (ref. 4). Such a gauge is capable of extending by approximately 5 orders of magnitude the low-pressure limit of a conventional triode ionization gauge.

In addition to the magnetic effect, considerable attention must be paid to the useful lifetime of a sealed-vacuum interrupter. Commercial leak detectors are not sensitive enough to detect small leaks that can result in significant loss of vacuum in an interrupter of this type over a period of many years. The reliability required in the electric-utility industry exceeds that needed elsewhere. The space effort has intensified the interest of both the public and industry in the reliability question. If vacuum interrupters are to be used in the electric-utility industry to any major extent, the reliability criterion, and with it the ability to detect very small flows of gases, will be among the foremost requirements for the successful eventual manufacture of a full line of vacuum interrupters.

Another area of overlap between NASA work and that of the vacuum-switch industry concerns the general cleanliness and care required in vacuum processing. Particles inside the switch, particularly those carrying oxygen in the form of oxides, are highly detrimental to the performance of the device. Elaborate techniques must be used to eliminate the possibility of any such occurrences. All welding seams must be free of oxides and free of holes. Potentially enclosed spaces must be degassed or provided with leakage pathways.

From this enumeration of problem areas, it is obvious that NASA is possibly exerting considerable influence on the future development of vacuum switches. The reader may wonder in what respect the vacuum interrupter is different from other vacuum devices such as radio and TV tubes. Those who are familiar with the art will see that there are areas of overlap and that the vacuum switch is not a totally new and different technology in every respect. This survey, however, was undertaken to point out the relationship of NASA work to the vacuum switch and thus to help make the electrical utility industry and the manufacturers of these devices aware of the technology that exists within NASA now and will exist in the future. Such technology can aid greatly in resolving questions of reliability, safety, and performance, and may have considerable economic significance.

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CHAPTER 2

Basic Ultrahigh-Vacuum Studies

NASA has sponsored two programs which deal directly with the basic technology underlying ultrahigh vacuum suitable for applications such as vacuum interrupters.

Its program entitled "Theoretical and Experimental Studies of the Underlying Processes and Techniques of Low Pressure Measurement" (ref. 5) includes both laboratory research in the general area of low-pressure measurement and a survey of current activities in aeronomy, particularly those involved with experimental studies of the neutral density and composition of the upper atmosphere. The first phase of the overall effort is related to problems in electrical vacuum switches, although the scientific objectives in the experimental program were established with aeronomy in mind.

The experimental program has included a careful investigation of several methods of measuring the gas pressure in ultrahigh vacuum. Certain anomalous effects which take place in ionization gauges in the presence of some molecular gases, notably oxygen, were selected for special study. Oxygen is one of the principal chemical elements which cause difficulties in vacuum circuit breakers. A paper entitled "Effects of Electron Surface Interactions in Ionization Gauges" (ref. 6) presents results of this study. In addition to this special study, a continued study of new and improved methods of measuring gas density was carried out. This included a comprehensive evaluation of the suppressor ionization gauge and a comparison of this gauge with other pressure-measuring devices. A similar comparison and evaluation of various types of mass analyzers was made. The present status of low-temperature electron sources also was studied. Any major advance in these areas would have profound implications regarding instrumentation techniques for the measurement of pressure.

A related NASA document entitled "Ultra-High Vacuum, A Survey" is of interest to the newcomer in the field (ref. 7).

The experimental work has included a major study which demonstrates and explains certain significant anomalous readings of ionization gauges in the presence of some molecular gases, particularly oxygen and carbon monoxide. Carbon monoxide is the major residual gas found in vacuum electrical switchgear. This is probably because the metals from which the device is constructed are degassed with the use of carbonaceous materials, particularly graphite. It is well known that the oxides of common metals can be reduced in this fashion.

Important conclusions from this work are—

(1) Large anomalous ion currents can flow to the collector of an ionization gauge and give an apparent pressure indication which is unrelated to the actual gas density in the volume of the gauge enclosure. Such currents can be sizable, particularly when the gauges are operated in an atmosphere containing oxygen (fig. 4).

(2) The anomalous readings can lead to a misleading interpretation of the data which decay with time when the gauges are removed from the oxygen, or vice versa. Such readings could easily be misinterpreted as outgassing of the vacuum gauge.

(3) Evidence has been collected that the effect is due to dissociative ionization by electron impact at the anode surface. At low-electron currents there is an enhanced rate of production

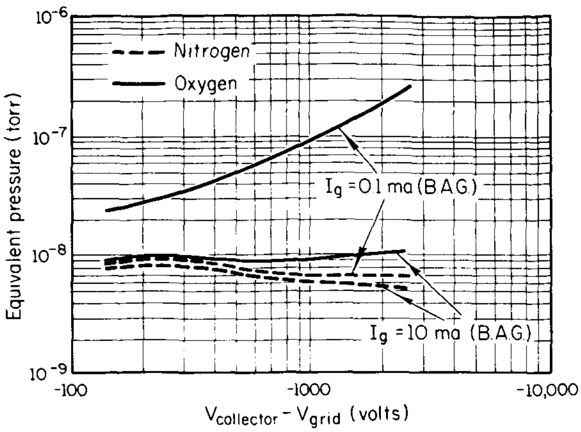


FIGURE 4.—Anomalous readings of oxygen pressure as a function of voltage in a Bayard-Alpert gage (B.A.G.).

of such ions accompanied by a reduced rate of collection in a Bayard-Alpert gauge.

(4) After a carefully controlled exposure to oxygen, anomalous currents corresponding to pressures of approximately 10^{-7} torr have been observed with an admission current of a few milliamperes. Following the removal of oxygen, the effect decays with a time constant which varies inversely with electron admission current.

(5) A number of effects in the presence of oxygen also give erroneous readings either in the ionization gauges or in mass analyzers. The composition of the gas may be altered both by chemical reactions at the hot filament and by electron bombardment of adsorbed gases.

This NASA research program has greatly clarified some important effects which have significant bearings on pressure measurements in general. Among the topics which remain for further industrial investigation are:

(1) Investigation of the specific physical mechanism by which ionization at the surface takes place for various gases and metals.

(2) Further study of desorption of gases by electron bombardment.

(3) Mechanisms by which oxygen is converted to CO in an ionization gauge.

(4) Design of an ionization gauge which does not exhibit these effects.

A continuing program of research in the ultrahigh-vacuum field in industry would be of considerable interest.

NEW METHODS OF PRESSURE MEASUREMENT

Under NASA contract a number of studies have been carried out to evaluate and compare the reliability and limitations of vacuum gauges for total and partial pressure. One involved the comparison between a magnetic deflection instrument (ref. 8) and a Philips Omegatron (ref. 9). Both were calibrated and compared with a Bayard-Alpert gauge in the region from 10^{-5} to 10^{-10} torr. In general, reasonable agreement was obtained, although under certain conditions the cracking pattern for molecular gases (O_2, CO) was found to vary with pressure in the magnetic deflection instrument, an effect which may be caused by surface ionization by electron impact.

An experienced operator is needed for both the magnetic deflection instrument and the Omegatron, since the peculiarities of each instrument are best learned by experience.

The use of a photocurrent suppressor gauge invented at the Coordinated Science Laboratory during 1962 (ref. 10) was also investigated. This gauge greatly reduces the X-ray photocurrent limitation of the Bayard-Alpert gauge while retaining many of its advantages. Linearity and reliability were demonstrated in the region of pressures from 10^{-5} to 5×10^{-12} torr.

THIN-FILM ELECTRON SOURCES

The necessity for a thermionic cathode in mass spectrometers and ion gauges often changes the composition of the gases measured by these instruments. Vacuum circuit breakers using vacuum arcs have been fitted with mass spectrometers and under some conditions very peculiar results have been obtained. Therefore a suitable cold-electron source which is inert with respect to its surroundings would be valuable. Such a source should not be damaged by a bakeout of the vacuum switch at temperatures up to at least 400° C, nor should it contribute extraneous materials to the system at these temperatures. For many useful experiments in electrical switchgear, a long service life would also be desirable.

When Mead (ref. 11) suggested the use of thin-film multilayer devices as electron sources, it looked as though a solution of this problem might be at hand. These emitters are three-layer devices consisting of an evaporated metal base, an insulating film only a few hundred Ångstroms thick, and a thin covering metal film operated a few volts positive with respect to the base. Attempts to fabricate such electron sources under a NASA contract were successful to the extent that electron emission was observed. After initial difficulties, much better cold cathodes were made by Cohen (ref. 12). Cesium was used to lower the work function of the outer metal film and thus increase the emission of the source by a factor of 10^5. This technique is very useful for a permanently evacuated tube, but would not be applicable to one that is baked out or opened to air after sensitization or to one operated under even moderate pressures of active gases. Generally speaking, however, for electrical switchgear these conditions are fulfilled and the work done under NASA contract on cathodes of that type appears to be directly applicable to industrial utilization.

Another program of interest in the development and production of electrical switchgear using ultra-high-vacuum techniques is described in two NASA contract reports, one dated July 1964 and the other November 1965, on work done at the Midwest Research Institute. The first report is entitled "Extreme Vacuum Technology (below 10^{-13} torr) and Associated Clean Surface Studies" (ref. 13). The second report is entitled "Extreme Vacuum Technology Developments" (ref. 14). Valuable information is also contained in the various quarterly reports that were written under this contract, No. NASr 63 (06). The first report deals with five phases as follows:

1. Development of Extreme Vacuum Technology Utilizing the Vapor Jet Mechanism and a Helium Permeation Guard Technique

A vapor-jet-test system was built to analyze experimental jet designs. The operational results indicate that the pump speed as well as the pressure differential across the jet vary directly with boiler pressure. The pumping speed reaches a peak and falls off long before the maximum pressure differential is attained. This problem could be solved by a two-boiler or combination jet arrangement.

A new helium guard for glass was developed which lowers the permeation of helium by 3 orders of magnitude. The technique which consists of treatment with cesium metal can easily be applied to existing glass systems as well. After the cesium treatment, the pressure in a special glass system using five stages of mercury vapor pumping fell below the detectable level of a commercial Redhead magnetron gauge. While this treatment is not directly applicable to vacuum switches as they are built today, the method indicates the way in which future development in industrial operations can alleviate this problem. This is therefore an example of a NASA-developed technique that is effective and unusual. Although it is not possible to take it into industry unchanged, NASA has opened the door to adaptations of a possible technique.

2. Determination of the Quantities and Species of Gas Above Ion Pumps and Chemically Trapped Oil Diffusion Pumps

The mass analysis of gases above an ordinary getter-ion pump has shown that only a limited capability exists to remove helium from the system and that the pump surfaces eventually become saturated. The surfaces can be reactivated, however, by a bakeout in vacuum at 455° C.

The gases above a chemically trapped oil diffusion pump were studied by means of a sensitive partial-pressure analyzer. It was shown that no oil components can be detected in the system if the chemical trap is at liquid nitrogen temperature. Trace amounts are detectable, however, if the trap is at room temperature. The residual gases in the system were methane, water, helium, hydrogen, lithium, carbon dioxide, carbon monoxide, nitric oxide, and oxygen. There was also a group of hydrocarbon materials with masses of 24, 25, 26, and 27. The amounts of these residual gases do not appear to be affected greatly by the chemical trap temperature. But it was noted that at liquid nitrogen temperatures, the mass spectrum characteristics of the pumping fluid were absent.

3. A Physical Adsorption Isotherm for Inert Gases (fig. 5)

The performance of a cryogenic vacuum system depends on the amount of gas that a cryopanel can adsorb. In this NASA work a new physical adsorption isotherm based on a triangular-site model was derived. This isotherm is linear for very low coverages, reduces to the Langmuir adsorption isotherm when there is only first-layer coverage, yields a superposition of two Langmuir adsorption isotherms when two layers are present, exhibits distinctive steps as each additional layer is condensed, and predicts finite film thicknesses for saturation pressures. The equations must be solved iteratively and have been programed for an IBM 1620 data processing system. It is hoped that this program

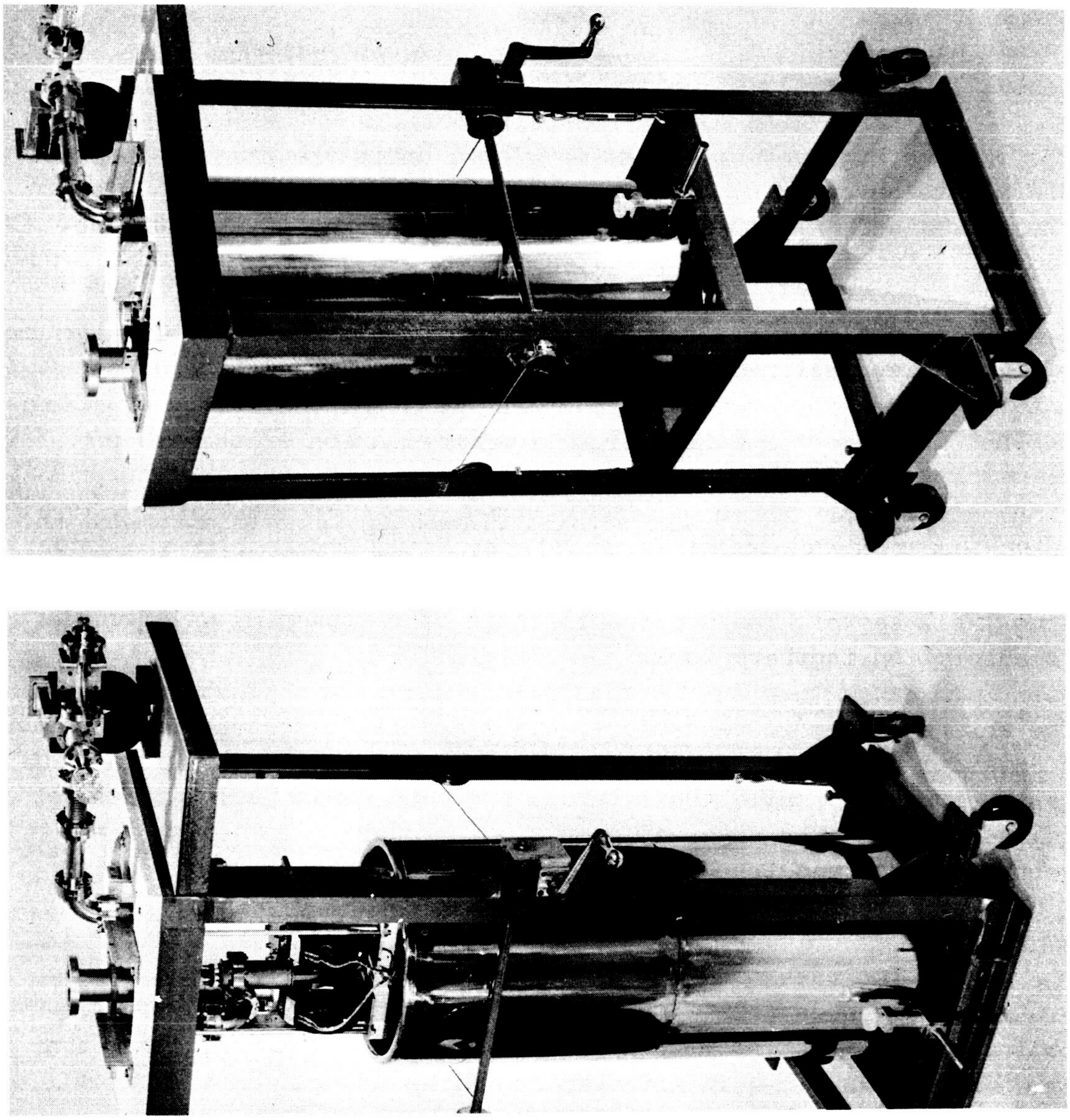


FIGURE 5.—Extremely high-vacuum system for experiments with liquid helium cryoponals, field emission microscopy, partial-pressure analysis, and UHV gages.

can be made available to industrial users. The results demonstrated how the theory could be used to design cryopanels economically for specific vacuum switch applications.

4. Development of a Total-Pressure Gauge for Pressures Below 10^{-12} Torr

Development of total-pressure gauges was carried out with commercial Redhead magnetron gauges (NRC type 552). The ion current-to-gas pressure response for helium deviated sharply from linearity below 7×10^{-10} torr (4×10^{-9} torr when corrected for the low-ionization sensitivity of helium). The response assumed a slope of 1.43 so that an indicated reading of 1×10^{-13} torr for helium should be corrected to 1.3×10^{-12} torr due to the nonlinear response and to 8.4 $\times 10^{-12}$ torr due to the low-ionization sensitivity of helium. After the treatment of the gauge elements with cesium, the sensitivity increased by a factor of 2 and the point of inflection moved down by a factor of 2. Another beneficial result of the cesium treatment was the ability to start the gauge instantaneously even at the lowest pressures.

5. The Adhesion of Metals Exposed to Vacuum and Thermal Outgassing

The tendency of the metallic electrodes in a vacuum switch to weld together by normal contact has prevented the consideration of any electrode configurations other than butt contacts for fear that the activating mechanism would not be able to break cold welds properly. Research in the physics of adhesion, closely related to ultrahigh-vacuum technology, is of direct consequence to this problem (fig. 6). If materials with low-adhesion tendencies can be used as current-carrying contacts, more favorable electrode geometries can be considered. The tendency for adhesion or cold welding of structural metals occurs as a result of vacuum and thermal outgassing. Stainless steel, aluminum, and titanium alloys were exposed at a pressure of 3×10^{-10} torr for 1000 hours and subjected to a 350° C thermal degassing treatment in a 10^{-8} torr vacuum for 100 hours. Specimens were tested with both the original texture and with polished surfaces. The sample faces were exposed during vacuum degassing and then brought into contact by rotating the vacuum system. The maximum angle of repose between the samples under the influence of gravity gave a measure of adhesion. No change occurred due to either vacuum exposure or combined thermal and vacuum outgassing. The theory for cold welding predicts welding between two surfaces when the formation of a common interface results in a lowering of the net free surface energy of the two materials. Therefore, metal surfaces with stable oxide layers would not be expected to cold-weld and this was verified in the experiment.

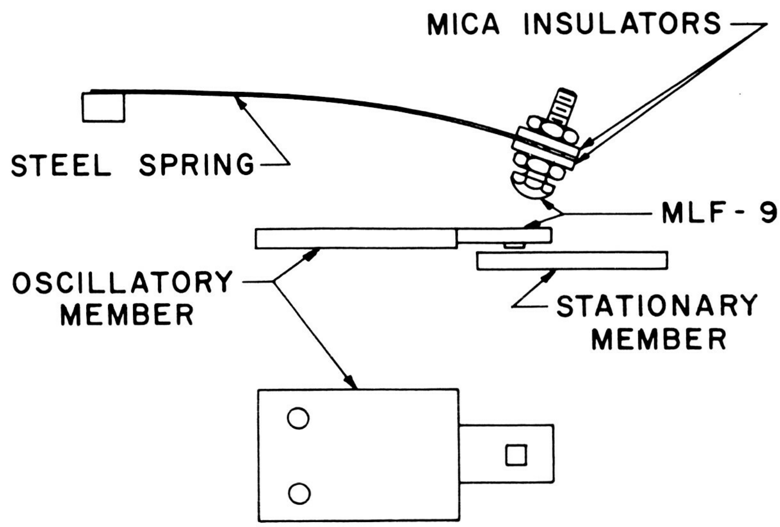
Additional work of interest for industrial applications has been done recently at Midwest Research Institute. It has progressed in the direction discussed above and is reported in NASA Cr–324 (ref. 15) as follows:

> Several phases relating to the attainment, measurement, and application of ultra-high-vacuum environments are reported. The phases covered are: development of a dual expansion nozzle for vapor-jet studies; determination of the gases present in UHV systems with oil diffusion and getter-ion pumping; measurements and theory on cryopanel operation; establishment of cold-welding criteria; and determination of response characteristics for extreme high vacuum gauges and field emission microscopes.
>
> A vapor nozzle with dual expansion chambers has been designed. Many people have dismissed the Forescu design on the basis of his ultimate pressure runs; however, those runs were vapor-pressure limited. The high velocity, low density upper jet does improve pump performance, but more definitive tests must be made.
>
> An analysis of the gas species present in a UHV system with getter-ion and oil diffusion pumping has shown many interesting comparisons. An important discovery was made regarding the operation of traps above oil diffusion pumps. A combined cryogenic and chemical trap has shown the ability to give more reliable and economical service.
>
> Experimental data for helium cryopumping at 4.28° K on a stainless-steel cryopanel has been obtained. In addition, the physical adsorption isotherm based on a triangular-site model has been improved in several ways. The energy contributions due to nearest neighbors have been evaluated on an improved model. The change in effective adsorption energy is notable. Predictions of the revised theory are presented.
>
> A guidelines study on cold welding has been performed. The results from three cases may be summarized as follows. For the ideal case, when molecularly smooth cleaved crystals are permitted to reheal, cold welding takes place due to the large area of contact which is re-formed at normal atomic lattice spacings. When structural metals with original or polished surfaces make touch contact

after exposure to simulated space environments, cold welding does not take place. When structural materials are subjected to vibrational contact under a 250-psi normal load, cold welding takes place to a greater extent in vacuum than at atmospheric pressure.

The response of magnetron gauges in their original form and with a cesiation treatment is reviewed. Numerous data have shown that a characteristic break from linearity and cutoff level exists for magnetron gauges and that the pressure values at which these characteristics occur can be lowered by a cesiation treatment. A field emission microscope has been constructed and tested.

Another NASA-supported program entitled "Adhesion Between Atomically Clean Metallic Surfaces," carried out at the Syracuse University Research Institute under the direction of Douglas V. Keller, Jr., is also of interest (ref.



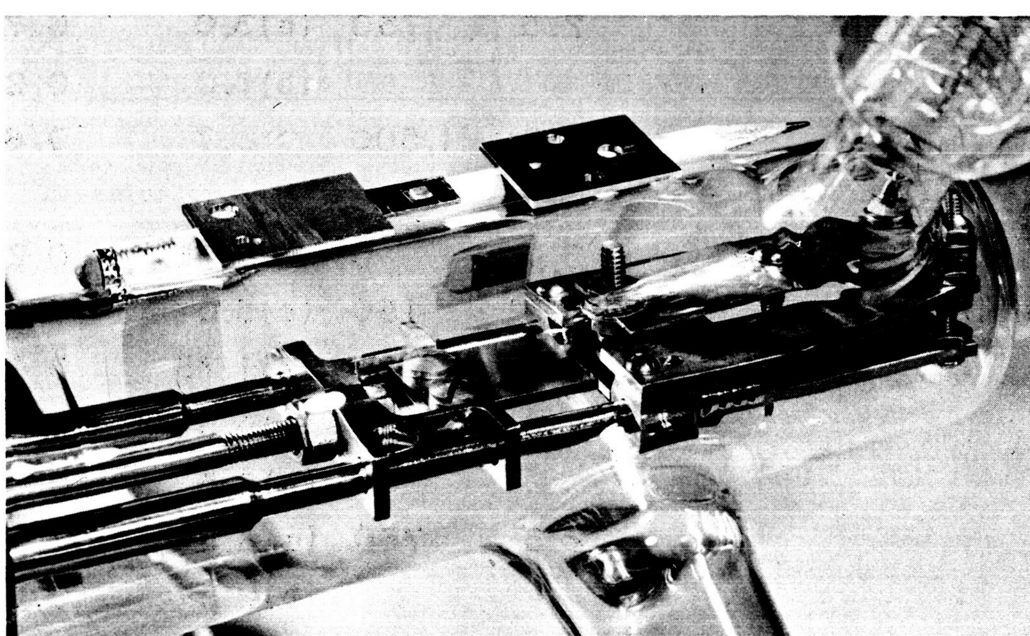


FIGURE 6.—Schematic and sideview of apparatus for vibratory cold-welding tests at the Midwest Research Institute.

16). In addition to a final report dated July 1, 1962, a Technical Note of the same title was published in February 1964 (ref. 17).

This research on adhesion bonding between metallic solids identifies the underlying interaction processes and mechanisms involved in the process of two atomically clean metallic surfaces being brought together and forming a stable interface. If these mechanisms can be understood sufficiently, the problem of seizure between metals in contact under vacuum can be solved by knowledgeable selection of materials. For instance, complete seizure is not necessarily the end result in a mechanical device exposed to high vacuum when the lubricant is used up.

Progress toward the solution of this problem may be readily separated into two distinct parts; i.e., theoretical analysis and experimental verification. In the NASA effort under discussion, the latter was somewhat limited, but progress was made in understanding the basic nature of the process of adhesion. A report of the experimental progress was given at the joint NASA–DOD symposium on "Space Lubrication," May 3, 1963, and published in the proceedings (ref. 18).

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CHAPTER 3

Adhesion Mechanism and the Effect of Surface Preparation

ANALYSIS OF ADHESION MECHANISM

Of particular interest to a vacuum interrupter designer are those areas of adhesion which deal with moving and sliding metallic parts of the electrodes and the electrode-operating mechanisms. Two electrode metals may be joined at room temperature through some physical or mechanical mechanism. Adhesion apparently is closely related to the general phenomenon of friction as well as to cold welding, and the greatest impetus for the NASA-supported studies probably is the increased metal-to-metal adhesion, i.e., increase in the coefficient of friction, as the atmospheric pressure is decreased to vacuum. The failure of conventional lubricants under vacuum can cause total seizure of bearings and other moving parts.

If the occurrence of adhesion can be reduced to a negligible value, or the mechanism can be understood well enough to make control feasible, there is little doubt that the remaining components of the frictional coefficient can be reduced by conventional design techniques. If it is possible to understand the true nature of adhesion, a better understanding of ordinary friction, cold welding, sintering, and possibly even grain boundary strength and fatigue may result.

A somewhat more detailed view may yield a broader conception of the problems. A limitation might conceivably be the adhesion or adsorption of a monolayer of metal atoms on a metallic substrate. This would fall under the category of metallic adsorption, or "sitting time" of an atom on a hot substrate. The next case might be one in which the layer would be built up into a bulk phase many atoms thick. Retention of metal to an undisturbed substrate by some type of chemical or electrostatic force is generally known as chemical adhesion. At the other end of the scale, mechanical interlocking of one phase to another occurs when the interlocks are of sufficient depth to create an interfacial bond. The surface free energy is defined as the reversible isothermal work required to pull apart in vacuum a 1-square-centimeter cross section of a material having perfect crystal structure. Modifications to this definition are necessary when gases are adsorbed on the surface which would lead to irreversible processes. These processes would cause a lowering of the available energy furnished by the breaking process.

Thus, chemical adhesion may be considered as part of the isothermal reversible work required to separate and replace to exact coincidence an interface in a perfect vacuum. The mechanical interlocking of surface irregularities constitutes a second type of adhesion which relies on the mechanical properties of the materials rather than on the interaction chemistry and is considered as mechanical adhesion. The ideal energy of adhesion would then be defined as the surface energy of the interfacial energy if two different materials are involved.

This definition assumes the return of the interface after it has been created to be ideal so that the surfaces must interact without an imposed mechanical force in perfect atomic coincidence. The energies in the ideal case are related to the cohesive energy of the solid with respect to the type of atomic bonds formed. For unrelated metal surfaces, the junction cannot be considered in chemical equilibrium as would be the case for a simple grain boundary where the electrochemical potentials of the components are equal. Although these conditions are quite unattainable by even the most careful experiments, and have little meaning for practical applications to friction or wear processes, consideration of them allows some insight into the nature of adhesion and aids in analysis of the adhesion data.

The various processes involved in metallic adhesion introduce a number of variables which are difficult, if not impossible, to control in experiments and therefore tend to complicate study of the fundamental phenomena. Probably the conditions necessary for a successful adhesion experiment involve the forceless interaction of two atomically clean surfaces at a temperature below the bulk diffusion range (fig. 7). The interatomic forces involved in the adhesion processes will be even more complex to analyze than those involved in simple solid surface energy problems, which are still unresolved in a mathematical sense. The immediate problems in a qualitative solution appear to be the establishment of a standard experiment which will meet the requirements discussed above within practical limitations, and a precise technique to estimate the actual area of metal-to-metal contact, as well as a method to resolve the interfacial crystal structure.

Until these problems are solved with greater accuracy, we will have to be extremely cautious in vacuum interrupter technology in regard to designs which involve sliding or rotating metallic surfaces inside the vacuum tube. Since this limitation considerably restricts the engineering of vacuum interrupter devices, industrial research laboratories should continue to develop expertise in this area and take over where NASA has left off.

A much less ambitious but practical NASA project on adhesion and cohesion of metals in

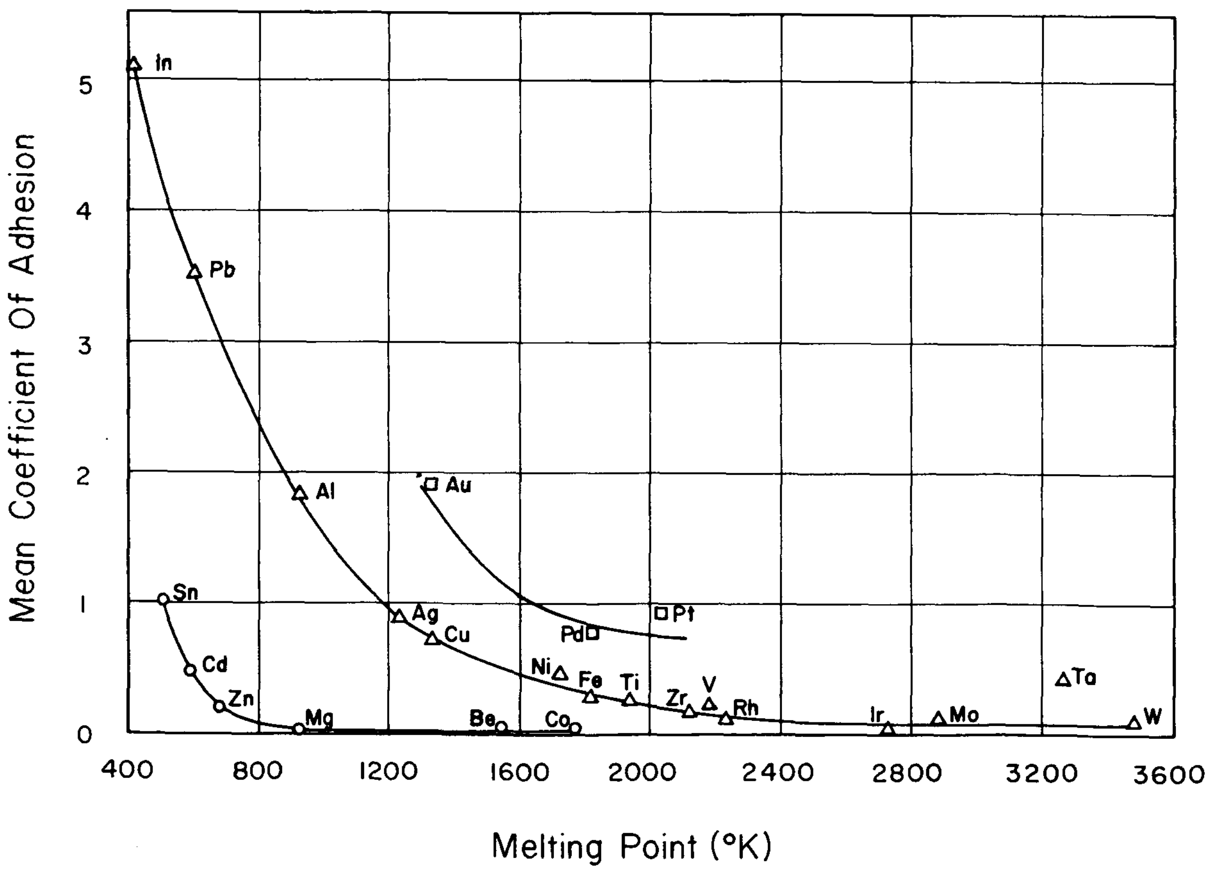


FIGURE 7.—Mean coefficient of adhesion versus metal melting point (after M. E. Sikorski, private communication).

ultrahigh vacuum was carried out at the National Research Corp. (ref. 19). The general objective was to obtain information as to the conditions under which metals and alloys will adhere to one another so tenaciously as to hinder the relative motion or separation of components of mechanical and electrical devices, such as bearings, solenoids, valves, sliprings, and mating flanges.

Techniques were developed under one contract (NASr–48) for evaluating the cohesion of metals at various temperatures by repeatedly fracturing and rejoining notched tensile specimens in ultrahigh vacuum. Two types of apparatus were used: a differential expansion device, and a screw-drive device. The latter was found to be the better. Maximum cohesion obtained at room temperature was about 65 percent for copper, 19 percent for 1018 steel, and 0 percent for hardened 52100 steel. Time in contact appears to be an important factor for copper at 200° C and above. Both 1018 and 52100 steel were found to be "self-cleaning" at 500° C, the former showing repeated readings near 100 percent cohesion, and the latter increasing in percent cohesion with each successive break at a temperature of 500° C.

Hardness was found to be an important variable with respect to cohesion. Copper or mild steel exhibited less and less cohesion when repeatedly fractured and rejoined even at ambient pressures too low to permit significant contamination in the available time. These initially soft metals were work hardened by this treatment and the successive reductions in cohesion are ascribed to this phenomenon. No cohesion could be measured on initially hard heat-treated 52100 steel at room temperature when tested in a similar manner.

Although many other variables such as temperature, time in contact, degree of deformation in compression, sliding, etc., are important, it was considered most practical to assess initially the tendency of various commonly used alloys to stick together at room temperature without sliding or severe deformation. It also was considered advisable to determine the behavior of clean surfaces before attempting to study the more complex behavior of contaminated surfaces. Exposure to vacuum alone at room temperature removes only a certain amount of physically absorbed gases, and heating in vacuum can be tolerated only to a mild degree when the effect of work hardening or of hardening by heat treatment is to be evaluated. The equipment was therefore modified to permit experimenting with a number of specimens successively without breaking the vacuum. Means for cleaning the surfaces of these specimens while under vacuum were also developed. The wire-brushing method was used successfully and some development of a second method, ion bombardment, was begun. The technique of successive fracture and rejoining eliminates the surface-cleaning problem and permits acquisition of data characteristic of the metal itself, but it is not applicable to dissimilar metal pairs. Both similar and dissimilar combinations of copper, copper-beryllium alloy, 1018 steel, 4140 steel, 440C steel, and titanium were studied. The specimens were cleaned by wire brushing and the following results were obtained:

Soft copper showed no tendency to adhere to itself or to steel, titanium, or Cu-Be alloy at 10^{-9} torr and room temperature after exposure to a pressure of 10^{-6} torr at 250° C even when severely deformed in compression.

Wire brushing at 10^{-9} torr after heating to 250° C at 10^{-6} torr can cause at least 6 percent cohesion between flat faces of soft copper, but not of soft steel at room temperature when slightly deformed in compression.

No cohesion occurs between specimens of soft steel or of soft titanium when severely deformed in compression at 10^{-9} torr after exposure at 10^{-6} torr at 250 ° C.

Much less cohesion occurs between pieces of soft copper after wire brushing in vacuum than after fracturing and rejoining in vacuum. This is a very important conclusion for workers with vacuum interrupter electrodes, since it would be highly desirable to make them of soft copper. Fracturing and rejoining in vacuum are likely to be encountered, however, and the feasibility of wire brushing or other artificial treatment would have to be investigated further.

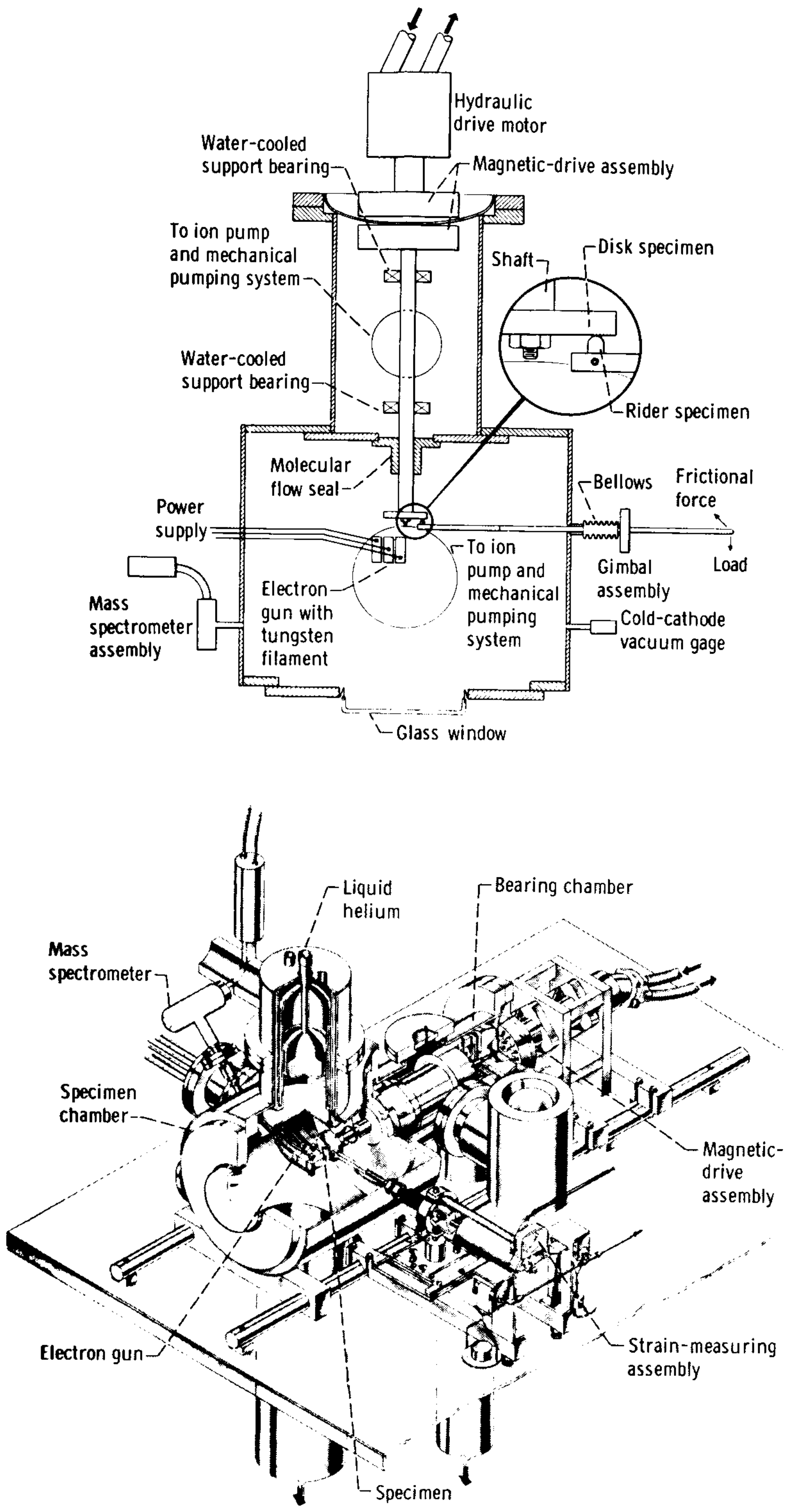
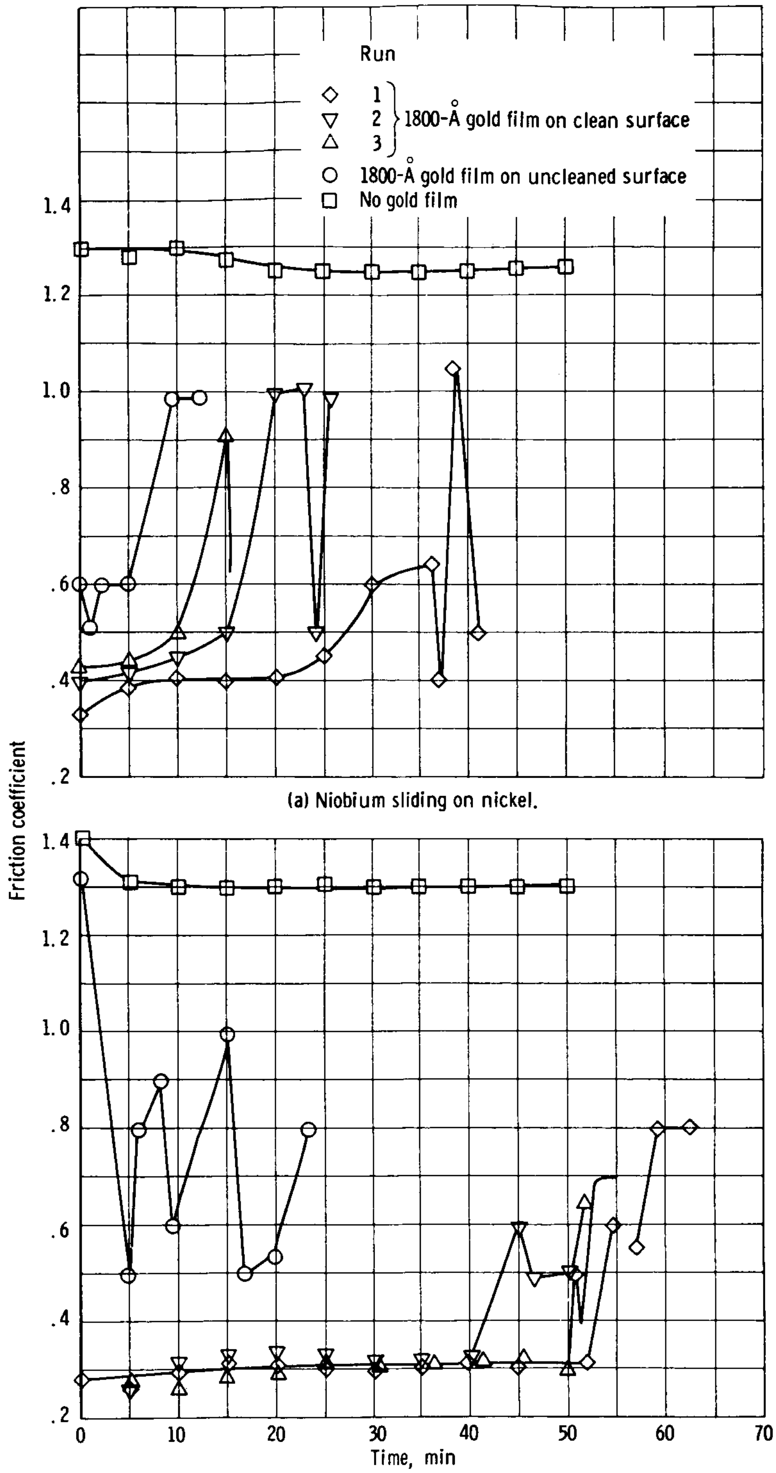


FIGURE 8.—Ultra-high-vacuum friction apparatus.



(a) Niobium sliding on nickel.

(b) Niobium sliding on nickel - 10-percent-chromium alloy.

FIGURE 9.—Friction coefficient of niobium on nickel and a nickel-chromium

SURFACE CLEANING AND LUBRICANTS

Adhesion and cohesion in vacuum are affected by methods of surface preparation and lubrication. The former was discussed at the 1964 SAE NAS Manufacturers Forum by R. A. Gaz, A. B. Kaufman, and P. H. Dutch of Litton Systems, Inc., in a paper entitled "Evaluation of Cleaning Processes Utilizing Radioisotopes." They studied different processes of cleaning surfaces by using radioisotopes to contaminate the specimens under test. A minute quantity of a radioisotope was deposited on the surface of the test specimen, which was checked for radioactivity by a Geiger-Muller counter before and after the cleaning. The ultrasonic cleaning processes evaluated consisted of a cascade series of numerous cleaning baths preceded by a degreaser step. A Turco bath was found to be the most effective cleaning agent. The optimum cleaning time was 2 minutes for the Turco bath, 3 minutes for a Tergitol bath, 4 minutes for a Trend bath, and 15 minutes for Chlorothene Nu. Applying a radioisotope to the surface parts is an effective method for determining the surface cleanliness. On the other hand, the data obtained may not represent the actual operating conditions unless adequate precautions are taken and may represent instead an evaluation of the decontamination of radioactive surfaces.

The related question of lubrication was investigated, at least with respect to one promising technique, by Talivalidis Spalvins and Donald H. Buckley at the Lewis Research Center; their techniques and results are reported in a NASA Technical Note (ref. 20). In this work, thin gold films were vapor deposited on nickel, nickel-chromium, and nickel-rhenium surfaces to be used for lubrication purposes. The durability of the film was determined by the characteristics of the friction coefficients. Durability and adhesion of the film on the substrate are essential when thin films are used as lubricants. The methods of substrate preparation for vapor deposition included mechanical polishing and electron bombardment (fig. 8). Friction experiments were conducted with a hemispherical niobium rider sliding on the deposited gold film on a rotating disk. Results of this investigation showed that the life of the films during friction experiments was increased when the substrate was electron bombarded and thermally etched prior to vapor deposition on the etched surface at an elevated temperature of 800° F. (fig. 9). A diffusion-type interface was believed to have formed between the film and the substrate. Nickel-chromium and nickel-rheium alloy substrates produced longer film durability in friction studies than did pure nickel substrates, presumably due to increased substrate hardness.

Pressure Measurements

The vacuum gauge is perhaps the most important single diagnostic device used in the development and manufacture of vacuum circuit breakers. It is needed not only to attain extremely good vacuum conditions during the manufacturing of the device and its components but also because it is customary to guarantee a reliable life of 20 years in electric-utility applications. What can happen in a critical situation was amply illustrated in New York in 1965. Failure to retain vacuum can outweigh all the other advantages that a vacuum switch might have.

NASA efforts in the art and science of vacuum diagnostics have given rise to numerous publications, among which several deal specifically with gauges and the associated equipment: "A Study of Some Aspects of Ultra-High Vacuum Measuring Equipment," by D. H. Holkeboer (ref. 21). "Absolute Pressure Gauge Feasibility Study by Micro-Erg Laboratories, Inc." (ref. 22); "A High Vacuum Gauge Calibration System," by W. S. Kreisman (ref. 23); Goddard Summer Workshop articles entitled "Vacuum Gauge Systems," by J. Gavis, and "Spacecraft Vacuum Gauge Comparison," by C. A. Baumgardner (ref. 24); and "The Use of a Helium Mass Spectrometer Leak Detector," by E. W. Young (ref. 25).

Holkeboer studied the calibration of ultrahigh-vacuum gauges using the double molecular leak method to establish known pressures. A dynamic system was used in which gas admission and exhaust were controlled by restrictions. Since the gas obeyed molecular-flow laws, the test pressure produced was proportional to the supply pressure applied to the inlet leak. The investigation was concerned principally with methods of reaching low background pressures of 3×10^{-11} torr, leak calibration methods, leak characteristics, and temperature effects on gauge calibration.

The leak material employed in this work, porous Vycor, exhibits a conductance which is independent of pressure up to 1 atmosphere, inversely proportional to the square root of absolute temperature and inversely proportional to the square root of molecular weight. The conductance of a given leak appears to be stable after proper conditioning.

Gauge temperature was also shown to be a factor of importance. The gauge readings for both total pressure and partial pressure are inversely proportional to the square root of the absolute temperature. An analysis of molecular-flow kinetics relating to gauge calibration was also carried out. (A valuable bibliography is given in app. I of ref. 21.)

The system described by Holkeboer is capable of gauge calibration at pressures ranging from 10^{-4} to 10^{-9} torr using argon, nitrogen, neon, or helium gas. The probable error is estimated to be ±6 percent or better.

Work at Micro-Erg Laboratories, Inc., was concerned with the operational and performance characteristics of a pressure gauge based on the phenomenon of momentum transfer from the gas measured. The principle of momentum transfer is well defined in terms of a fundamental model of rarefied gases and the definition of pressure associated with it. Measurements were found possible down to 10^{-10} torr with instrumentation using state-of-the-art components.

Although a meaningful assessment of the potential utility of this gauge must await further laboratory evaluation, this study did not disclose any basic limitations other than the radiation bias pressure. The gauge is not very complicated and there is ample choice in design to meet a variety of application requirements.

Absolute and relative calibration of newly developed types of pressure gauges poses a considerable problem, which is treated by W. S. Kreisman as well as J. Gavis. While Micro-Erg Laboratories, Inc., established proportionality constants by taking advantage of the complementary aspects of drag and radiometric sensing techniques, Kreisman employed three specially designed, bakable McLeod gauges with overlapping pressure ranges as pressure standards in the region from 20 torr to 1×10^{-4} torr. Theoretical accuracies of 1 percent or better are expected for the McLeod gauge readings in this pressure region. Pressures from 1×10^{-4} to 10^{-7} torr can be measured, but the accuracy of the readings depends on adsorption and outgassing effects. Kreisman has given results pertaining to the reproducibility of measurements and comparisons of various gauge readings. A technique for measuring pressure rise was used to determine how the vacuum gauges and other system components were behaving.

Gavis attempted to extend measurements of a similar nature to lower pressures by the technique of pressure division. During the last few weeks of the Goddard Summer Workshop, three separate comparison runs were made using this method. Enough data were accumulated to establish confidence in the pressure-division method as a basis for the comparison of vacuum gauges. Baumgardner has discussed evaluation of an ultra-high-vacuum calibration system built for Goddard in 1961 by the National Research Corp., and Young has described the pressure-testing and vacuum-testing methods of leak detection as a function of time.

CHAPTER 5

Cathode and Arc Phenomena

The exact mechanism by which an arc is maintained in vacuum is still a matter of considerable discussion.

The most complete description of the processes at the cathode during a vacuum arc has been given by Von Engel and Robson (ref. 26). Briefly, their theory considers the cathode spot of the arc to be divided into several regions. In region 1, electrons from the cathode are accelerated by field and potential distributions, which are determined by positive space charge. For mercury, the thickness of this region is predicted to be about 3 orders of magnitude smaller than the diameter of the spot. The density of neutral atoms in region 1 is very large, and ions, being accelerated toward the cathode by the fields primarily in region 1, scatter many of the evaporating atoms back to the cathode surface. Von Engel and Robson show that many of the atoms being scattered back to the cathode surface are in excited states. The release of electrons from a metal by the impact of excited atoms is a highly efficient process.

In region 2, there still exists a large vapor density, but here the electrons have gained sufficient energy to produce excitation. As a result of inelastic collisions, electrons of lower energy are present in large numbers, neutralizing the positive-ion space charge to a large extent, so that the electric field is much lower than in region 1. The very high velocities observed for plasma plumes in vacuum arcs are caused by elastic scattering of electrons in the vapor, primarily in region 2. It is thought that a large electron pressure is set up in region 2 because of the scattering processes. On the upper side of region 2 the electron pressure is sustained by elastic collisions between electrons and atoms, with the result that the evaporating atoms are accelerated away from the cathode in the gradient of the electron pressure.

Von Engel and Robson use their theory to compute the cathode-fall potential of a mercury arc, arriving at a value of 8.6 volts, which agrees extremely well with the commonly measured value of 8 volts. In nearly all of the literature associated with vacuum arcs, there is a great deal of speculation about the state of ionization of the plasma plume leaving the cathode spot. For example, Reece arrives at the conclusion, based primarily on measurements of the energy delivered to the anode and to the cathode during an arc, that for each ion emitted from the cathode spot, 10 atoms are emitted and 100 electrons are emitted. Von Engel and Robson conclude that a similar proportionality should exist in the mercury arc. NASA work pertaining to this subject is still underway. Preliminary data regarding these mechanisms for materials similar to tungsten were obtained under contract NAS 3–5915 (ref. 7), which deals with the possibility of using laser-induced ionization mechanisms as an ion source. Another NASA-supported investigation entitled "Thermal Analysis of Anode and Cathode Regimes in an Electric Arc Column" (ref. 28) deals with the fluctuating arc mode and the phenomena associated with striking and restriking of arc spots.

Of a more basic nature, but of equal significance to the ultimate understanding of arc phenomena, are the transport cross sections for electrons in various metallic vapors. A NASA contract entitled "Electron Collision Cross Sections in Metal Vapors" (ref. 29) is a typical example of the type of investigation needed in this field.

The Townsend α-coefficient and electron drift velocity are being measured in alkali-helium mixtures as a function of E/p, the ratio of electric field to total pressure, and N/N_{He}, the ratio of alkali to helium density. By comparing the measured values with the results of a numerical solution of the Boltzmann equation using assumed cross sections, cross sections consistent with the measurements are obtained. A total excitation cross section for cesium having a peak value of 1.15×10^{-14} cm^2 at 8 eV has been obtained from the experiments. Similar measurements for potassium are in progress.

CHAPTER 6

Hardware Development

NASA-SUPPORTED VACUUM SWITCHGEAR DEVELOPMENT

The Lewis Research Center asked for the development of electric switchgear for space nuclear electrical systems under contract NAS 3–2546, and the Missile and Space Division of the General Electric Co. recommended the use of vacuum interrupters. The final report of this study (ref. 30) covers theoretical investigations of welding, material selection, and other requirements for vacuum interrupter electrodes. It also deals with experimental studies of switchgear technology development, including contact-welding investigations and high power ac and dc interruption tests. Conceptual designs are given for an ac circuit breaker and a dc engine contactor. A number of requirements not applicable to commercial devices, such as shields against cesium vapor, high temperature ambient, and protection against nuclear radiation damage, are covered. The study dealt not only with the interrupter itself but also with mounting, activating mechanisms, and related accessories. It was pointed, however, toward specific hardware requirements, viz, an ac circuit breaker required to interrupt 1000-volt, 3-phase, 600-ampere, 2000-cps current, which was accomplished by a 1-inch-diameter electrode configuration and a ¼-inch opening. The engine contactor was designed for 10 kV, 10 ampere direct current, which required a ½-inch-diameter tungsten contact.

PRESENT STATUS OF COMMERCIAL DEVICES

The number of vacuum interrupters on the market has increased considerably in the last few years. The General Electric Co., Jennings Radio Co. (fig. 10), Allis-Chalmers Manufacturing Co., and Line Material Industries (fig. 11) are offering vacuum interrupters for sale. Selected examples of various types are listed in the Appendix with the technical details and, in some cases, requirements for operation and mounting.

One foreign manufacturer, the Associated Electrical Industries, Inc., offers a vacuum interrupter for motor contactor application having a current rating of 300 amperes continuous, a voltage rating of 3.3 kV at a frequency of 50 to 60 cps. The Tokyo Shibaura Electric Co. (Toshiba) has also published a catalog of a series of vacuum switches. Other manufacturers in Japan and the United States are also known to be working on devices having ratings similar to those listed in the appendix. The General Electric Co. has stated that it expects to develop vacuum interrupters with ratings as high as 34.5-kV working voltage and interrupting capability of 40 to 50 kA. These figures seem to be

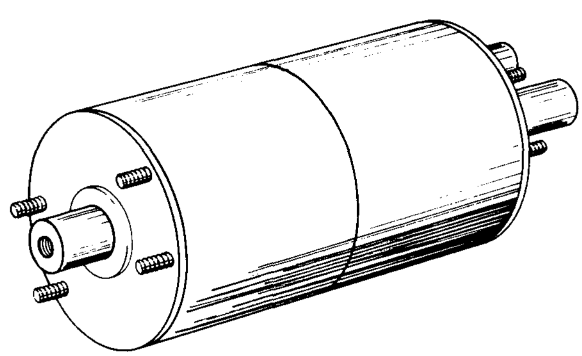


FIGURE 10.—Outline of Jennings vacuum power interrupters type 903B and 904B.

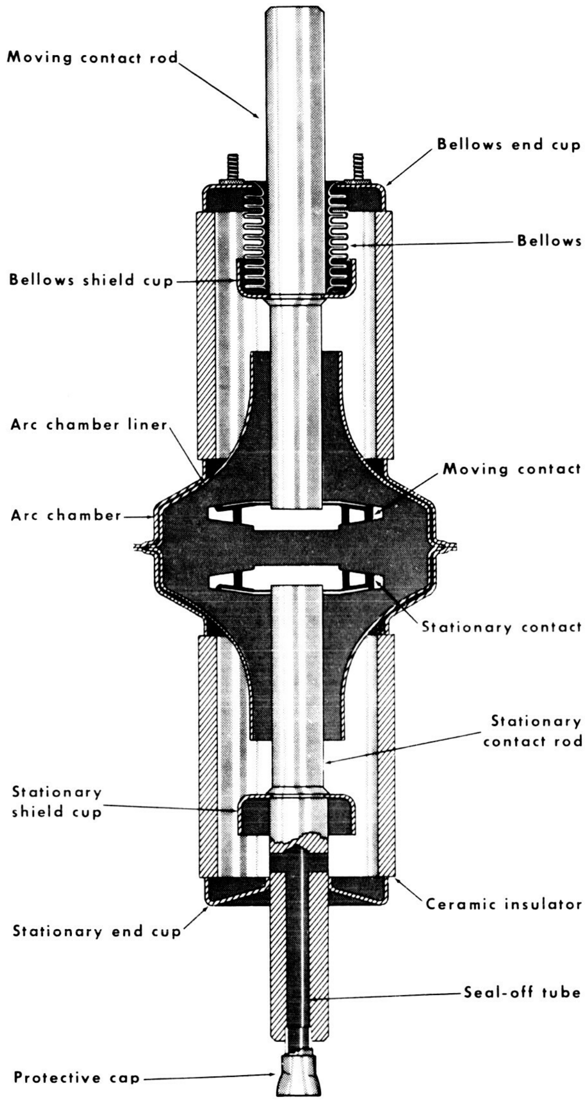


FIGURE 11.—Cutaway of type VSA vacuum interrupter of Line Material Industries.

the highest so far proposed for any vacuum-interrupter application.

Beyond this voltage, vacuum interrupters may be placed in series. Such equipment is built, for instance, by the Hi-Voltage Equipment Co. Vacuum switches with modest ratings have been manufactured for a long time for the electronics industry by such firms as Jennings Radio Co. However, the future market potential is expected to be in motor control, transformer tap changers, reclosers, and, particularly, metal-clad switchgear, with high-voltage transmission applications a possibility in the more distant future.

Both domestic and foreign manufacturers are likely to be involved in the production of vacuum interrupters for these applications. The author hopes that the material collected in this report of NASA contributions to the technology will stimulate research and development of vacuum-interrupter devices for the benefit of the general public, and lead to even better service by the electrical industry.

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Unclassified NASA and NASA-sponsored publications may be consulted at these Federal regional technical report centers: University of California, Berkeley; University of Colorado Libraries, Boulder; Library of Congress; Georgia Institute of Technology, Atlanta; The John Crerar Library, Chicago; MIT, Cambridge, Mass.; Linda Hall Library, Kansas City (Mo.); Columbia University, New York; Carnegie Library of Pittsburgh; Southern Methodist University, Dallas; and the University of Washington Library, Seattle.

Such publications also are sent to public libraries in Anchorage, Baltimore, Birmingham, Boston, Bridgeport, Brooklyn, Buffalo, Charlotte (N.C.), Cincinnati, Cleveland, Dayton, Detroit, Denver, Fort Worth, Hartford, Kansas City (Mo.), Little Rock, Los Angeles, Miami, Memphis, Milwaukee, New Orleans, Oakland, Oklahoma City, Phoenix, Pittsburgh, Rochester, San Diego, San Francisco, San Antonio, St. Louis, St. Paul, Seattle, Toledo, Trenton, and Wilmington.

Some NASA publications are available for purchase from the Clearinghouse for Federal Scientific and Technical Information Center, Springfield, Va. 22151; others from the Clearinghouse for Federal Scientilc and Tech-Printing Office, Washington, D.C., 20402.

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Appendix

PRELIMINARY SPECIFICATIONS—GENERAL ELECTRIC POWER-VAC VACUUM INTERRUPTER

PV–09A–04–15L06 and PV–09B–04–15L06

Customer outline drawing (Model A)	0123B1749
Customer outline drawing (Model B)	0123B1738
Frequency rating	50/60 cycles
Maximum line-to-line voltage	15.5 kV
Continuous current carry	400 amperes
Capacitance switching current	400 amperes
Interrupting current, symmetrical	6000 amperes
Momentary	20 000 amperes with 100-lb contact force 40 000 amperes with 400-lb contact force
Low-frequency withstand	60 kV
BIL	110 kV
Maximum arcing time to interruption	0.018 sec
Operating life in terms of contact erosion	0.25 in.
Life at maximum interrupting rating	200 operations
Mechanical life	20 000 operations
Shelf life	20 years
Weight of interrupter	3.6 lb
Recommended operating characteristics:	
Contact stroke	⅜ in.
Moving contact weight	0.6 lb
Contact closed force	100 lb for 20 000 amperes, momentary 400 lb for 40 000 amperes, momentary
Normal force due to atmospheric pressure	20 lb
Operating speed (minimum average to ¼-in. gap)	3 to 4 fps
Maximum overtravel	0.285 in.
Closing speed	2.5 to 3.5 fps
Maximum contact bounce duration	0.002 sec

NOTE: Life values are typical, since erosion is dependent on bounce characteristics of mounting and mechanism. External adjustment to maintain contact force is required at intervals to obtain the indicated long-contact life at the higher current values.

SPECIFICATIONS—GENERAL ELECTRIC POWER-VAC VACUUM INTERRUPTERS

PV–01A–06–15A12

Customer outline drawing	0104B3397
Frequency rating	50/60 cycles
Maximum line-to-line voltage	15.5 kV
Continuous current carry	600 amperes

Capacitance switching current	600 amperes
Interrupting current, symmetrical	12 000 amperes
Momentary	20 000 amperes with 100 -lb contact force
Low-frequency withstand	60 kV
BIL	110 kV
Maximum arcing time to interruption	0.018 sec
Operating life in terms of contact erosion	0.12 in.
Life at maximum interrupting rating	100 operations
Generated heat loss at 500 amperes	15 W
Mechanical life	10 000 operations
Shelf life	20 years
Weight of interrupter	13.3 lb
Recommended operating characteristics:	
Contact stroke	½ in.
Moving contact weight	1.75 lb
Contact closed force	100 lb for 20 000 amperes, momentary
Normal force due to atmospheric pressure	35 lb
Opening speed (minimum average to ⅜-in. gap)	4 fps
Maximum overtravel	⅜ in.
Closing speed	2.5 to 3.5 fps
Maximum contact bounce duration	0.002 sec

Note: Life values are typical, since erosion is dependent on bounce characteristics of mounting and mechanism. External adjustment to maintain contact force is required at intervals to obtain the indicated long-contact life at the higher current values.

SPECIFICATIONS AND RATINGS FOR VSA–102B VACUUM INTERRUPTER—LINE MATERIAL INDUSTRIES

A. *Voltage ratings*

Nominal voltage	14.4 kV
Maximum design voltage	15.5 kV
Dielectric withstand 1.5-40 μsec surge (BIL)	110 kV
60 cycle dry, 1 min	50 kV
RIV at 1000 kc, maximum	8 mV

B. *Current ratings*

Continuous current	560 amperes
Symmetrical interrupting capacity (2.4 to 15.5 kV)	12 000 amperes
With duty cycle shown below:	
2.4 to 4.8 kV	12 000 amperes
3.3 to 14.4 kV	10 000 amperes

Duty cycle:

Percent of rating	X/R ratio	Number of operations
16–20	3	112
45–55	7	30
90–100	15	40
Total		232

Maximum capacitor switching rating	560 amperes
Maximum arcing time	1 cycle
Maximum resistance at 560 amperes	30 microhms

C. *Frequency rating*	50 to 60 cycles

D. *Application requirements to achieve above ratings.* Optimum results will be achieved by consulting Line Material engineers regarding design of operator for this interrupter.

E. *Physical characteristics*

Weight	6 lb
Mechanical life	10 000 operations

SPECIFICATIONS—JENNINGS VACUUM INTERRUPTER

Type RP 100

Normal line-to-line voltage (50/60 cps)	15.5 kV rms
Maximum recommended recovery voltage	32 kV rms
Continuous current	200 amperes, rms
Interrupt capacitive load	200 amperes, rms
Interrupt current symmetrical	2000 amperes, rms
Momentary (see contact pressure)	20 000 amperes, rms; 10 cycles
Momentary	12 000 amperes, rms; 1 sec
1-min withstand	36 kV, rms
BIL	95 kV
Maximum arcing time to interrupt	0.010 sec (½ cycle)
Maximum contact erosion	1/16 in.
Mechanical life at ¼-in. gap	20 000 close-open cycles
Shelf life	20 years

Mechanical requirements for operation

Weight of interrupter	2.38 lb
Weight of moving contact only	0.25 lb
Opening force to ¼-in.	12 lb
Contact pressure (contact closed force)	100 lb for 20 000 amperes momentary
Contact opening	5/32- to ¼-in. maximum
Overtravel	⅛ in.
Recommended contact opening time (5/32-in. gap)	0.015 sec maximum (average $V \cong 1.5$ fps)
Recommended contact closing time	0.030 sec maximum (average $V \cong 0.75$ ft/sec) (closing on load current) 0.015 sec maximum (average $V \cong 1.5$ ft/sec) (closing on fault current)
Contact bounce (closing on fault)	Less than 0.002 sec for maximum contact life

Applications. Underground load switching, capacitor bank switching, transformer switching, loop switching, general duty load switching. Can be used in series for higher voltages.

SPECIFICATIONS—JENNINGS VACUUM INTERRUPTER

Types RP 900

Normal line to line voltage (50/60 cps)	15.5 kV, rms
Maximum recommended recovery voltage	36 kV, rms

Continuous current	600 amperes, rms
Interrupt capacitive load	600 amperes, rms
Interrupt current symmetrical	4000 amperes, rms
Momentary (see contact pressure)	20 000 amperes, rms 10 cycles
	30 000 amperes, rms 10 cycles
	40 000 amperes, rms 10 cycles
Momentary	20 000 amperes, rms; 1 sec
1-min withstand	50 kV, rms
BIL	110 kV
Maximum arcing time to interrupt:	
Load current	0.008 to 0.010 sec; ½ cycle
Fault current	0.016 to 0.020 sec; 1 cycle
Maximum contact erosion	1/16 in.
Mechanical life at ¼-in. gap	50 000 close-open cycles
Shelf life	20 years
Mechanical requirements for operation	
Weight of interrupter (total)	7¾ lb
Contact pressure (contact closed force)	100 lb for 20 000 amperes, 10 cycles, and 1-sec momentary
	150–200 lb for 30 000 amperes, 10 cycles
	400 lb for 40 000 amperes, 10 cycles
Contact opening	¼ to ⅜ in. maximum
Overtravel	⅛ in.
Recommended contact opening time (¼-in. gap)	0.010 sec maximum (average $V \cong 2$ fps)
Recommended contact closing time	0.015 sec maximum (average $V \cong 1.5$ fps) (closing on fault current)
Contact bounce (closing on fault)	Less than 0.002 sec for maximum contact life

Applications. Underground load switching, capacitor bank switching, transformer load switching, transmission line switching, general duty load switching. Can be used in series for higher voltages.

SPECIFICATIONS—JENNINGS VACUUM INTERRUPTER

Types RP 102

Normal line-to-line voltage (50/60 cps)	15.5 kV, rms
Maximum recommended recovery voltage	32 kV, rms
Continuous current	300 amperes, rms
Interrupt capacitive load	200 amperes, rms
Interrupt current (symmetrical)	4000 amperes, rms
Momentary (see contact pressure)	20 000 amperes, rms; 10 cycles

Momentary	12 000 amperes, rms; 1 sec
1-min withstand	36 kV, rms
BIL	95 kV
Maximum arcing time to interrupt	0.010 sec, ½ cycle
Maximum contact erosion	1/16 in.
Mechanical life at ¼-in. gap	20 000 close-open cycles
Shelf life	20 years

Mechanical requirements for operation

Weight of interrupter	2.38 lb
Contact pressure (contact closed force)	100 lb for 20 000 amperes, momentary
Contact opening	¼ in. maximum
Overtravel	⅛ in.
Recommended contact opening time (¼-in. gap)	0.015 sec maximum (average V≅1.5 fps)
Recommended contact closing time	0.030 sec maximum (average V≅0.75 fps) (closing on load current) 0.015 sec maximum (average V≅1.5 fps) (closing on fault current)
Contact bounce (closing on fault)	Less than 0.002 sec for maximum contact life

Applications. Underground load switching, recloser and sectionalizing, capacitor bank switching, transformer switching, loop switching, general duty load switching.

SPECIFICATIONS—JENNINGS VACUUM INTERRUPTER

Types RP 904

Normal line to line voltage (50/60 cps)	5 kV, rms
Maximum recommended recovery voltage	15 kV, rms
Continuous current	600 and 800 amperes, rms
Interrupt capacitive load	600 amperes, rms
Interrupt current symmetrical	8000 amperes, rms
Momentary (see contact pressure)	20 000 amperes, rms; 10 cycles 30 000 amperes, rms; 10 cycles 40 000 amperes, rms; 10 cycles
Momentary (70-lb contact pressure)	50 000 amperes, peak; ½ cycle
1-min withstand	36 kV, rms
BIL	60 kV
Maximum arcing time to interrupt:	
Load current	0.001 to 0.010 sec; ½ cycle
Fault current	0.016 to 0.020 sec; 1 cycle

Maximum contact erosion	1/8 in.
Mechanical life at 1/4-in. gap	1×10^6 close-open cycles
Shelf life	20 years

Mechanical requirements for operation

Weight of interrupter (total)	7 3/4 lb
Contact pressure (contact closed force)	100 lb for 20 000 amperes, 10 cycles, and 1 sec momentary 150 to 200 lb for 30 000 amperes, 10 cycles 400 lb for 40 000 amperes, 10 cycles
Contact opening	1/4 to 3/8 in. maximum
Overtravel	1/8 in.
Recommended contact opening time (1/4-in. gap)	0.010 sec, maximum (average $V \cong 2$ fps)
Recommended contact closing time	0.015 sec, maximum (closing on fault current) (average $V \cong 1.5$ fps)
Contact bounce (closing on fault)	Less than 0.002 sec for maximum contact life

Applications. Medium voltage motor control. Power transformer and voltage regulator load tap changer.

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